

Interference of thermal photons from quark and hadronic phases in relativistic collisions of heavy nuclei

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We explore the intensity correlations for thermal photons having $K_T \leq 2$ GeV/c, for central collisions of heavy nuclei at RHIC and LHC energies. These photons get competing contributions from the quark and the hadronic phases. This competition gives rise to a unique structure, especially in the outward correlation function, due to the interference between the photons from the two sources. The temporal separation of the two sources provides the life time of the system and their strengths provide the relative contribution of the two phases. The results are found to be quite sensitive to the quark-hadron phase transition temperature and the formation time of the plasma.

I. INTRODUCTION

The last two decades have witnessed a concerted and a well co-ordinated theoretical and experimental effort to produce and study quark-gluon plasma - the deconfined strongly interacting matter, in relativistic collisions of heavy nuclei. The eminent commissioning of the Large Hadron Collider (LHC) at CERN and various upgrades, both in the accelerator and the detection systems, at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven will offer further opportunities to advance our understanding of the physics of this novel state of matter, which permeated the early universe. We have already been rewarded with the discovery of the jet-quenching [1, 2], the elliptic flow [3, 4], and the successful formulation of the partonic recombination [5] as a model for hadronization in recent experiments at RHIC. The thermal photons radiated from such collisions are being studied to determine the high temperatures reached in these collisions [6, 7, 8, 9].

The next step in this endeavour involves a critical examination of our concepts about the formation and the evolution of the plasma. An important question in this connection is how quickly, if at all, does the plasma thermalize; so that we can use the powerful methods of hydrodynamics to model the evolution of the system. Theoretical estimates for the thermalization time (τ_0) vary considerably and experimental observables like elliptic flow of hadrons only suggest that $\tau_0 \sim 1.0$ fm/c. A more quantitative experimental determination of τ_0 would be very valuable. One would also like to know the lifetime of the interacting system. Can we determine the temperature at which the phase transition takes place?

The quantum statistical interference between identical particles emitted from these collisions is expected to provide valuable inputs for the space-time description of the system. The use of photons for these studies admits several advantages. Firstly, they interact only weakly with the system after their production. Thus, they are not subjected to distorting effects such as re-scattering and Coulomb interactions which affect the results for hadrons. Secondly, and even more importantly, photons are emitted from every stage of the collision dynamics.

These aspects give us a hope of getting a direct information about the earliest, hot and dense stage of the system by studying the photons having larger transverse momenta, K_T . Recently, some additional sources of large K_T photons have also been proposed [10, 11].

The difficulty, of-course, arises from a meager emission of direct photons which lie buried in the huge background of decay photons. So far only one measurement involving photons having very low K_T by the WA98 Collaboration [12] for the central collision of lead nuclei at CERN SPS has been reported.

On the other hand, the theory of the intensity interferometry of photons from relativistic heavy ion collisions has been pursued in considerable detail by several authors [13, 14, 15]. It is generally felt that the experimental efforts for these studies have a larger likelihood of success at RHIC and LHC energies because of larger initial temperature of the plasma and a large suppression of pions due to jet-quenching. Of late, there have also been tremendous advances in methods for identification of single photons [8].

In the present work, we focus our attention on the photons having intermediate $K_T \approx 0.2 - 2$ GeV/c. The photons having $K_T \ll 2$ GeV/c will mostly originate from the hadronic phase of the system. They are expected to reveal a source which should be strongly affected by the flow and expansion of the system. The photons having $K_T \gg 2$ GeV/c should unveil a source which is in the infancy of the hot and dense quark-gluon plasma, and where the flow has just started to develop. The photons having $K_T \leq 2$ GeV/c are unique. They have their origin either in the hot and dense quark phase of the system or in the relatively cooler but rapidly expanding hadronic phase, where a large build-up of the radial flow boosts their transverse momenta.

We shall see that this leads to a rich structure in the correlation function for thermal photons especially when studied as a function of the outward momentum difference (q_o , see later), due to the interference of the two sources. The two sources also manifest in the correlation functions for the longitudinal (q_l) and sideward (q_s) momentum differences. This renders the correlation very sensitive to the formation time of the plasma. An early

formation and thermalization would provide a large initial temperature, while a late formation and thermalization will lead to a smaller initial temperature. This analysis can also help to find the fractional contributions of the quark and the hadronic phases to the single photon spectrum.

Since the interference mentioned above is controlled by the relative contributions from the quark and the hadronic phases, which in turn are decided by the critical temperature used in the model, we find a unique sensitivity of the results to the temperature at which the phase transition takes place.

We discuss the basic formalism in the next section. The results for RHIC and LHC energies are discussed in sect. III and IV respectively. In sect. V we discuss the sensitivity of our results to the initial formation time of the plasma and the transition temperature. Finally, we summarize our findings in sect. VI.

II. FORMULATION

One can define the spin averaged intensity correlation between two photons with momenta \mathbf{k}_1 and \mathbf{k}_2 , emitted from a completely chaotic source, as:

$$C(\mathbf{q}, \mathbf{K}) = 1 + \frac{1}{2} \frac{|\int d^4x S(x, \mathbf{K}) e^{ix \cdot \mathbf{q}}|^2}{\int d^4x S(x, \mathbf{k}_1) \int d^4x S(x, \mathbf{k}_2)} \quad (1)$$

where $S(x, \mathbf{K})$ is the space-time emission function, and

$$\mathbf{q} = \mathbf{k}_1 - \mathbf{k}_2, \quad \mathbf{K} = (\mathbf{k}_1 + \mathbf{k}_2)/2. \quad (2)$$

We shall use hydrodynamics to model the evolution of the system. The space-time emission function S is approximated as the rate of production of photons, $\text{EdN}/d^4x d^3k$, from the quark and the hadronic phases.

The interference between the thermal photons from quark and the hadronic phases is best studied by writing the source function S as $S_Q + S_H$ in the numerator, where Q and H stand for the two phases respectively, and then including either one, or the other, or both.

We shall discuss the results for the correlation function $C(\mathbf{q}, \mathbf{K})$ in terms of the outward, sideward, and longitudinal momentum differences, q_o , q_s and q_ℓ . Thus writing the 4-momentum as k_i^μ of the i th photon, we have

$$k_i^\mu = (k_{iT} \cosh y_i, \mathbf{k}_i) \quad (3)$$

with

$$\mathbf{k}_i = (k_{iT} \cos \psi_i, k_{iT} \sin \psi_i, k_{iT} \sinh y_i), \quad (4)$$

where k_T is the transverse momentum, y is the rapidity, and ψ is the azimuthal angle. Defining the difference and the average of the transverse momenta,

$$\mathbf{q}_T = \mathbf{k}_{1T} - \mathbf{k}_{2T}, \quad \mathbf{K}_T = (\mathbf{k}_{1T} + \mathbf{k}_{2T})/2, \quad (5)$$

we can write [13],

$$\begin{aligned} q_\ell &= k_{1z} - k_{2z} \\ &= k_{1T} \sinh y_1 - k_{2T} \sinh y_2 \end{aligned} \quad (6)$$

$$\begin{aligned} q_o &= \frac{\mathbf{q}_T \cdot \mathbf{K}_T}{K_T} \\ &= \frac{(k_{1T}^2 - k_{2T}^2)}{\sqrt{k_{1T}^2 + k_{2T}^2 + 2k_{1T}k_{2T} \cos(\psi_1 - \psi_2)}} \end{aligned} \quad (7)$$

$$\begin{aligned} q_s &= \left| \mathbf{q}_T - q_o \frac{\mathbf{K}_T}{K_T} \right| \\ &= \frac{2k_{1T}k_{2T} \sqrt{1 - \cos^2(\psi_1 - \psi_2)}}{\sqrt{k_{1T}^2 + k_{2T}^2 + 2k_{1T}k_{2T} \cos(\psi_1 - \psi_2)}}. \end{aligned} \quad (8)$$

The radii corresponding to the above momentum differences are often obtained by approximating the correlation function as,

$$C(q_o, q_s, q_\ell) = 1 + \frac{1}{2} \exp \left[- (q_o^2 R_o^2 + q_s^2 R_s^2 + q_\ell^2 R_\ell^2) \right]. \quad (9)$$

We also define the root mean square momentum difference $\langle q_i^2 \rangle$ as,

$$\langle q_i^2 \rangle = \frac{\int (C - 1) q_i^2 dq_i}{\int (C - 1) dq_i}, \quad (10)$$

so that for the Gaussian parameterization given in Eq. 9, we have

$$R_i^2 = \frac{1}{2 \langle q_i^2 \rangle}. \quad (11)$$

Thus, $1/[2 \langle q_i^2 \rangle]^{1/2}$ becomes a useful measure when the correlation function has a more complex nature as we shall see later.

We consider central collision of gold and lead nuclei, corresponding to the conditions realized at the RHIC and LHC, respectively. We assume that a thermally and chemically equilibrated quark-gluon plasma is produced at an initial time τ_0 . We further assume an isentropic expansion of the system to estimate the initial temperature, T_0 , in terms of particle rapidity density. Thus,

$$\frac{2\pi^4}{45\zeta(3)} \frac{1}{A_T} \frac{dN}{dy} = 4aT_0^3 \tau_0, \quad (12)$$

where A_T is the transverse area of the system, dN/dy is the particle rapidity density, and $a = 42.25\pi^2/90$ for a plasma of massless quarks (u, d, and s) and gluons. The number of flavours for this purpose is taken as ≈ 2.5 to account for the mass of the strange quarks. For the present work we shall mostly consider $\tau_0 = 0.2 \text{ fm}/c$ and give illustrative results for τ_0 varying from 0.2 to 1.0 fm/c, keeping dN/dy (or the total entropy) fixed. We add that, for study of thermal photons a value close to 0.2 fm/c may be more appropriate. The initial energy density is taken as a weighted sum of wounded nucleon and binary collision distributions as in earlier studies [16]. The

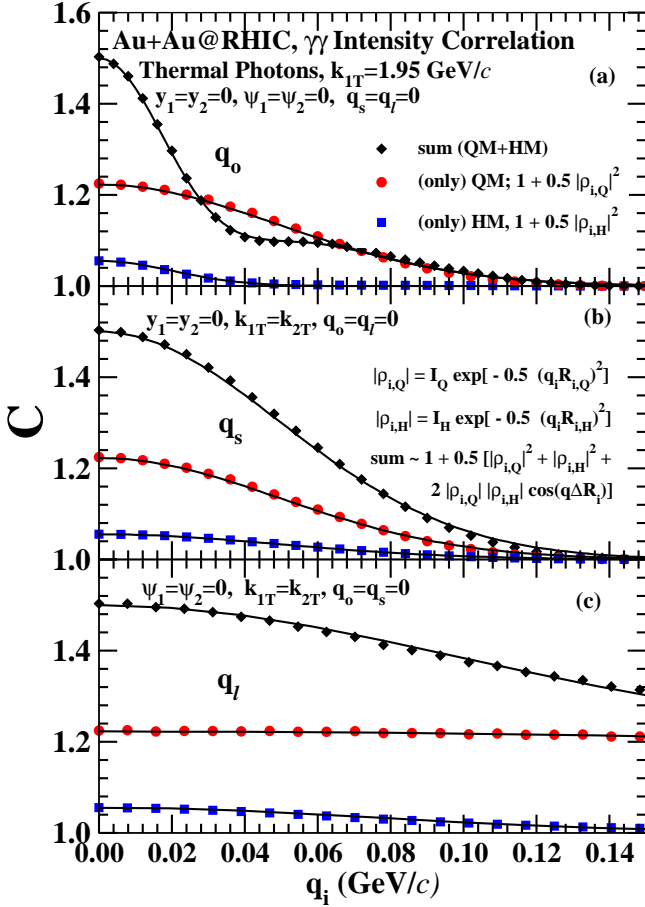


FIG. 1: (Colour on-line) (a) The outward, (b) sideward, and (c) longitudinal correlation functions for thermal photons produced in central collision of gold nuclei at RHIC taking $\tau_0 = 0.2$ fm/c. Symbols denote the results of the calculation, while the curves denote the fits.

quark-hadron phase transition is assumed to take place at a temperature of 180 MeV, while the freeze-out takes place at 100 MeV. The relevant hydrodynamic equations are solved under the assumption of boost-invariant longitudinal and azimuthally symmetric transverse expansion using the procedure discussed earlier [17] and integration performed over the history of evolution. We use the complete leading order results for the production of photons from the quark matter [18], and the results from Turbide *et al.* [19] for radiation of photons from the hadronic matter. A rich equation of state with the inclusion of all the particles in the particle data book, having $M < 2.5$ GeV/c² describes the hadronic matter. We take dN/dy at $y = 0$ as 1260 [11] for 200A GeV Au+Au collisions at RHIC and 5625 [20] for 5.5A TeV Pb+Pb collisions at LHC. A smaller value for the particle rapidity density at LHC may perhaps be more appropriate, though. This will, however, not change the nature of the findings reported here.

III. RESULTS FOR RHIC ENERGIES

As a first step, in Fig. 1 we have shown the outward, sideward, and longitudinal correlation functions for thermal photons at RHIC having $K_T \approx 2$ GeV/c. The 4-momenta of the two photons are chosen so that when we study the outward correlations, the q_s and q_ℓ are identically zero and the dependence on q_o is clearly seen, and so on. We first discuss the results when only the hadronic matter contribution or only the quark matter contribution is included in numerator (Eq. 1). We find that the correlation functions for the two phases can be approximated as:

$$C(q_i, \alpha) = 1 + 0.5 |\rho_{i,\alpha}|^2 \quad (13)$$

where $i = o, s,$ and ℓ , and α denotes quark matter (Q) and hadronic matter (H) in an obvious notation. The source distribution $|\rho_{i,\alpha}|$ is very well described by,

$$|\rho_{i,\alpha}| = I_i \exp[-0.5 (q_i^2 R_{i,\alpha}^2)] \quad (14)$$

where,

$$I_Q = \frac{dN_Q}{(dN_Q + dN_H)}, \quad (15)$$

and

$$I_H = \frac{dN_H}{(dN_Q + dN_H)}. \quad (16)$$

The final correlation function denoted by ‘sum’ in the figures can be approximated as:

$$C(q_i) = 1 + 0.5 [|\rho_{i,Q}|^2 + |\rho_{i,H}|^2 + 2 |\rho_{i,Q}| |\rho_{i,H}| \cos(q_i \Delta R_i)] \quad (17)$$

which clearly brings out the interference between the two sources [21]. Here ΔR_i stands for the separation of the two sources in space-time and q is the 4-momentum difference. For thermal photons having $K_T \approx 2$ GeV/c at RHIC, various radii (in fm) are obtained as:

$$\begin{aligned} R_{o,Q} &= 2.8, \quad R_{o,H} = 7.0, \quad \Delta R_o = 12.3, \\ R_{s,Q} &\approx R_{s,H} = 2.8, \quad \Delta R_s \approx 0., \\ R_{\ell,Q} &= 0.3, \quad R_{\ell,H} = 1.8, \quad \Delta R_\ell \approx 0. \end{aligned} \quad (18)$$

These results imply [21] that, while the spatial separation of the two sources is negligible, their temporal separation is about 12 fm. This gives the life-time of the system. If the mixed phase is of shorter duration or absent, this will obviously decrease.

This is seen more clearly in Fig. 2 where we have plotted the K_T dependence of ΔR_o and the outward, sideward, and longitudinal radii for the hadronic and the quark-matter sources of photons, obtained using the above procedure. We see that the outward, sideward and the longitudinal radii for the quark contribution depend weakly on the transverse momentum, indicative of only

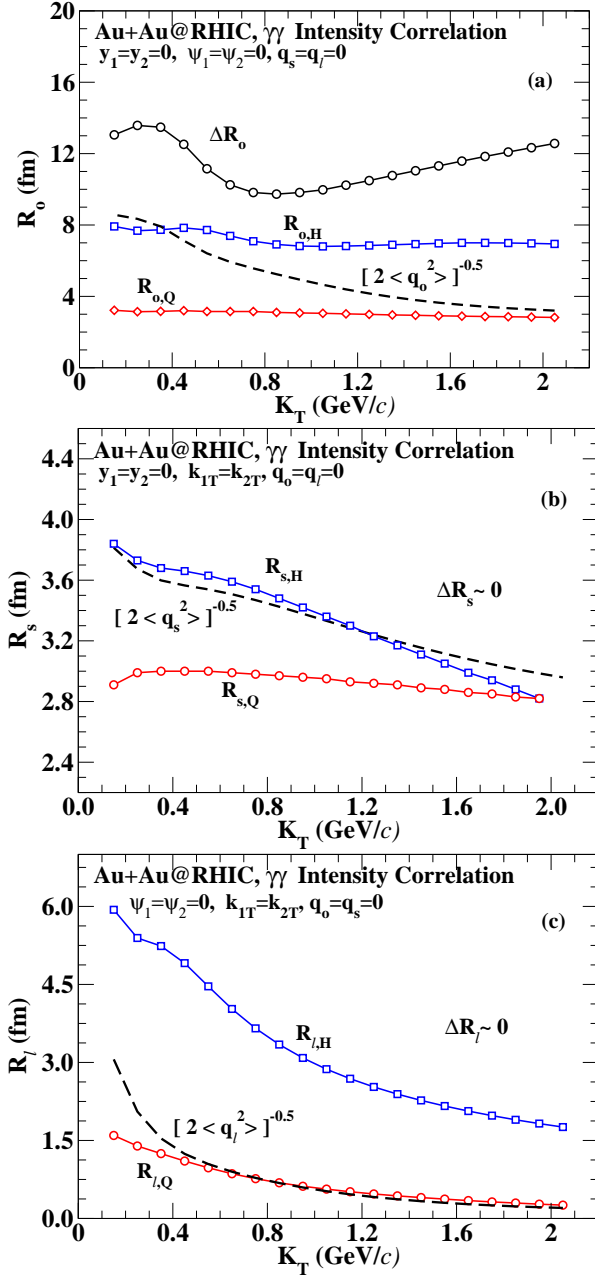


FIG. 2: (Colour on-line) Transverse momentum dependence of (a) the outward radii and temporal duration along with (b) the sideward and (c) the longitudinal radii for the hadronic and quark-matter sources obtained by fitting the final correlation function for thermal photons at RHIC energy. The radii determined from the root mean square momentum difference for the correlation function are also given for a comparison [13].

a mild development of the flow during that phase. The corresponding radii for the hadronic contribution show a stronger dependence on the transverse momentum, which is indicative of a more robust development of the radial flow during the hadronic phase. The duration of the source reveals a very interesting structure, and in fact

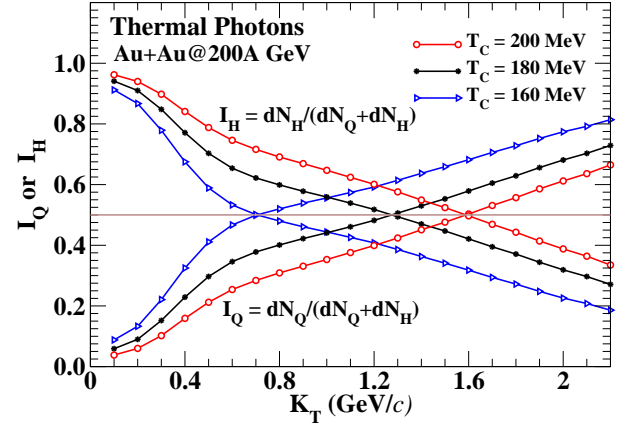


FIG. 3: (Colour on-line) Transverse momentum dependence of fraction of thermal photons from quark matter (I_Q) and hadronic matter (I_H) at RHIC energy. The solid curves give the results for $T_c = 180$ MeV, while the dashed and dot-dashed curves give the results for T_c equal to 160 and 200 MeV respectively. (see text).

it rises slightly at higher transverse momenta as the photons emitted during the hadronic phase benefit from the strong radial flow to greatly increase their transverse momenta. The saturation in ΔR_o towards low K_T has its origin in the competition between radial expansion and the decoupling of hadronic matter as it cools down below the freeze-out temperature at the edges.

The inverse root mean square momentum which, as we commented earlier, is a measure of the correlation radius, is seen to vary rapidly with K_T , for the outward correlation due to rapid variation of the competing contributions of the quark matter and hadronic matter phases. For the sideward correlation, it goes over smoothly from a value which is close to that for the hadronic matter at lower K_T to that for the quark matter at higher K_T , as one would expect. (The slight difference of $1/[2 \langle q_s^2 \rangle]^{1/2}$ from $R_{s,Q} \approx R_{s,H}$ at large K_T is due to the deviation of the calculated correlation function from a perfect Gaussian, to which it is fitted.)

As the fractions of the quark matter and the hadronic matter contributions play such a pivotal role in the momentum dependence of overall correlation function, we study them next. The fractions I_Q and I_H taken from the calculations for the single photon spectra are shown in Fig. 3, along with their dependence on the critical temperature. We shall discuss the importance of this dependence a little later.

In order to understand these interesting results more clearly, we have plotted the source-functions as a function of the transverse distance and time for thermal photons having $K_T \approx 0.5, 1.0$, and 2.0 GeV/c, in Fig. 4 and Fig. 5. In all the cases we see that the radial distributions for the QGP as well as for the hadronic phase are centered at r_T near zero and that the source function for the hadronic phase extends considerably beyond the same for the QGP phase. This of-course is only to be expected, due to the

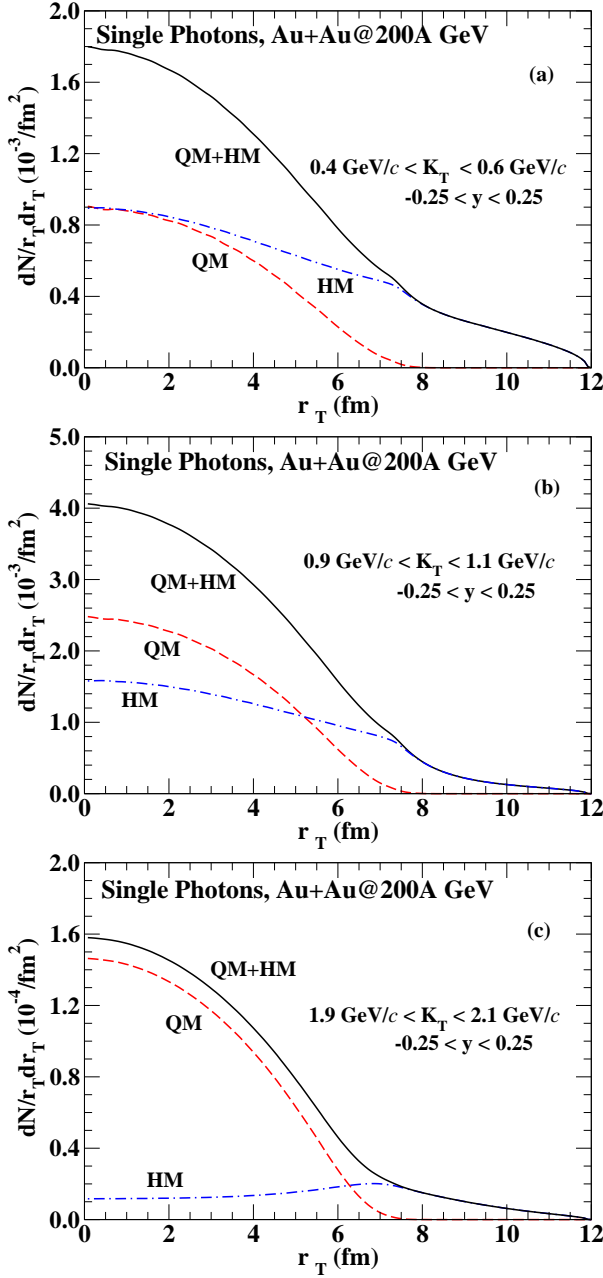


FIG. 4: (Colour on-line) The radial dependence of the source distribution function for emission of photons having transverse momenta of (a) 0.5, (b) 1.0, and (c) 2.0 GeV/c at RHIC energy.

large transverse expansion of the system. We also note a good yield of thermal photons from the hadronic phase at larger radii. In fact, one can notice a slightly enhanced emission at larger radii compared to that from the central region for $K_T = 2 \text{ GeV}/c$. This, as we noted earlier, arises due to the large kick received by the photons due to the radial expansion, leading to the blue-shift of their transverse momenta. The relative importance of the two contributions will depend on K_T and the transition temperature and lead to a rich structure in the resulting cor-

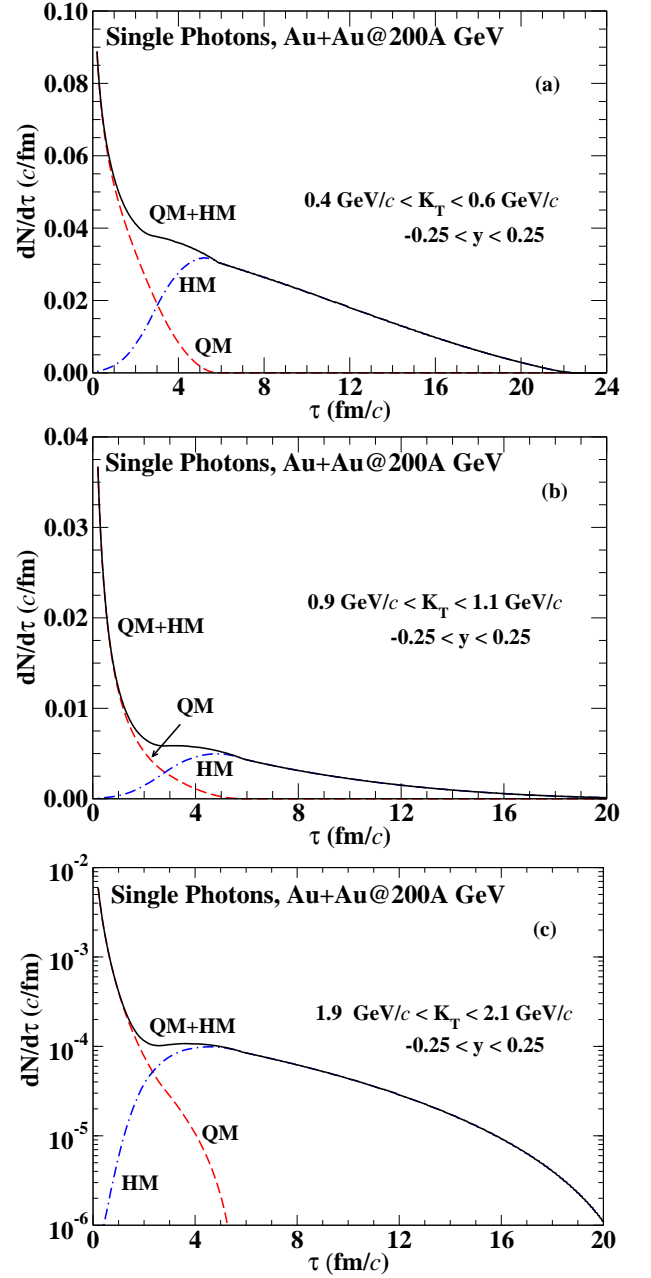


FIG. 5: (Colour on-line) The temporal dependence of the source distribution function for radiation of photons having transverse momenta of (a) 0.5, (b) 1.0, and (c) 2.0 GeV/c at RHIC energy.

relation function. However, note that the second term in the source of photons from the hadronic matter becomes important at larger K_T , where the contribution of the hadronic phase to photons is rather small, and thus it could be difficult to detect this effect.

Even a more valuable insight is provided by the temporal structure (Fig. 5) of the emission of photons from the QGP and the hadronic sources; the latter emerging after a lapse of some time, which the system spends in the QGP phase. The duration over which the photons from

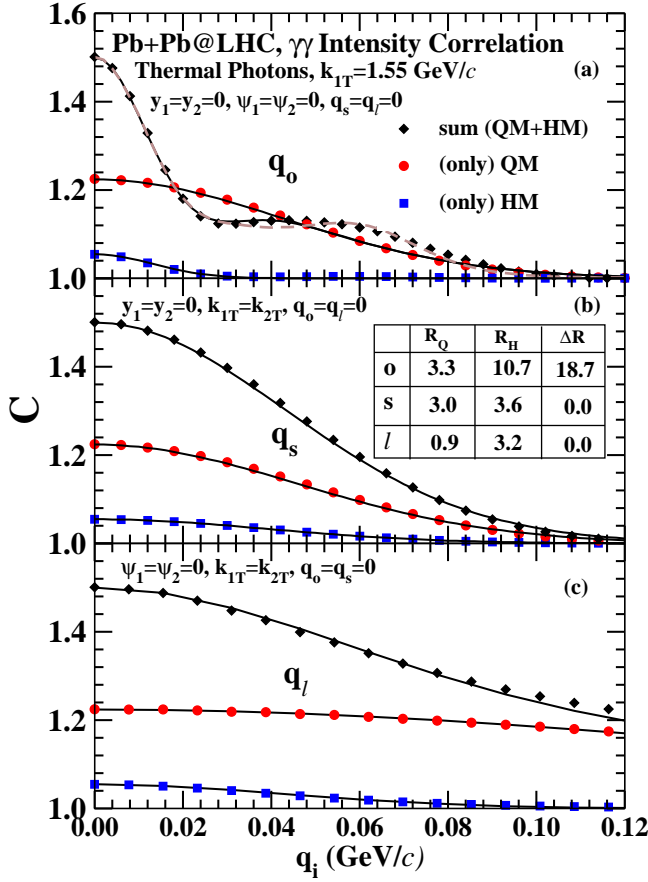


FIG. 6: (Colour on-line) Same as Fig. 1 for Pb+Pb at LHC.

the hadronic phase are emitted is quite large and essentially controls the parameter ΔR_o . It is worth recalling that the temporal structure of the source function seen here is qualitatively similar to the one seen in nucleus-nucleus collisions at cyclotron energies [21].

IV. RESULTS FOR LHC ENERGIES

The Large Hadron Collider will study collisions of lead nuclei at unprecedented energies of 5500 GeV/A. It is expected that the initial temperature likely to be attained reached in such collisions would be much higher than that at RHIC energies. This would provide a golden opportunity to study the properties of the QGP and the dynamics of its evolution. A larger initial temperature would lead to a larger duration of the interacting system, which in turn will provide an ample opportunity to the mechanism of expansion to develop. We can thus expect to put our models about the evolution of the interacting system to a very rigorous test.

In Fig. 6 we show our results for the intensity correlation of thermal photons having $K_T \approx 1.5$ GeV/c produced at LHC. We see, as before, an interference of the photons from the hadronic and QGP phases of the

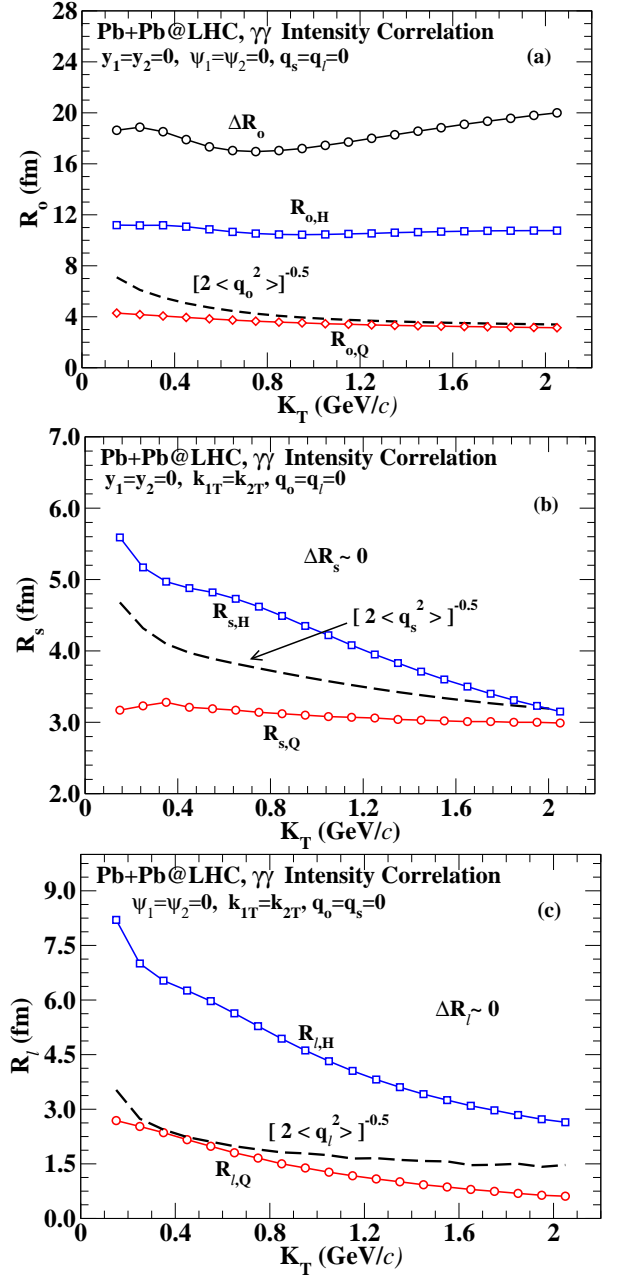


FIG. 7: (Colour on-line) Transverse momentum dependence of (a) the outward radii and temporal duration along with (b) the sideward, and (c) the longitudinal radii for the hadronic and quark-matter sources obtained by fitting the final correlation function for thermal photons at LHC energy. The radii determined from the root mean square momentum difference for the correlation function is also given for a comparison [13].

system. We add that the fit to the calculated values for the outward correlation function can be improved considerably (see dashed curve) by adding one more Gaussian term, centered at $q_0 \approx 0.06$ GeV/c in the source term for the hadronic matter, or by approximating $\rho_{o,H} \approx \sqrt{2(C_H - 1)}$, where C_H is the corresponding correlation function obtained numerically. We are trying

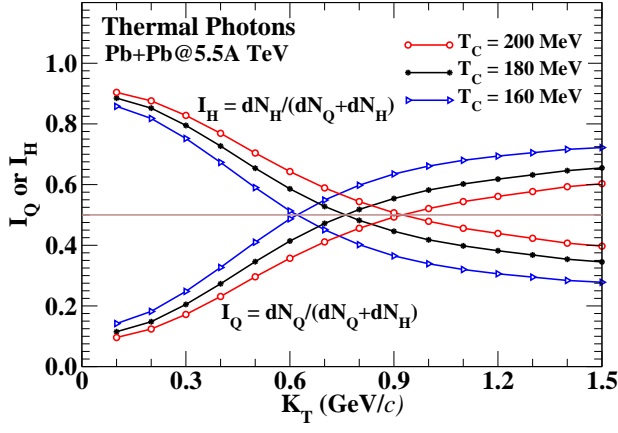


FIG. 8: (Colour on-line) Transverse momentum dependence of fraction of thermal photons from quark matter (I_Q) and hadronic matter (I_H) at LHC energy. The solid curves give the results for $T_C = 180$ MeV, while the dashed and dot-dashed curves give the results for T_C equal to 160 and 200 MeV respectively.

to understand this observation.

The results for $C(q_s)$ and $C(q_\ell)$ are similar in nature to those found at RHIC energy. We note that now the temporal separation of the two sources is about 19 fm/c (see inset Fig. 6).

Next we discuss the K_T dependence of the correlation radii (Fig. 7). We see a behaviour which is qualitatively similar to the one obtained earlier, though all the correlation radii are larger, specially ΔR_o which gives the duration of the source. We do emphasize here that $1/[2\langle q_i^2 \rangle]^{1/2}$ is closer to $R_{i,Q}$ at LHC due to the dominance of quark matter contribution even at modest K_T .

In Fig 8, we have plotted the fractions of momentum dependence of quark and hadron contribution at LHC energies, at three transition temperature T_C ($= 160, 180$, and 200 MeV). Comparing these results with those of Fig. 3, we see once again that decreasing T_C increases the fraction of photons coming from the quark matter. We also note that the transverse momentum where the quark and hadronic contributions become equal is quite sensitive to the transition temperature T_C . Realizing that, in an ideal situation we would be able to decompose the outward, sideward, and longitudinal correlations into two sources and that their intercepts on the y-axis will give I_Q and I_H , this opens up the tantalizing possibility of determination of the transition temperature, the two fractions becoming equal at K_T .

We next discuss the spatial (Fig. 9) and temporal (Fig. 10) distribution of source function for photons having $K_T = 0.5, 1.0$, and 2.0 GeV/c produced in central collision of Pb nuclei at LHC energy. Even though we note that the source distributions at LHC are qualitatively similar to those at RHIC, the extension of the hadronic sources beyond those for the quark sources (Fig. 9) and enhanced production at larger r_T from hadronic sources are amplified considerably here. The

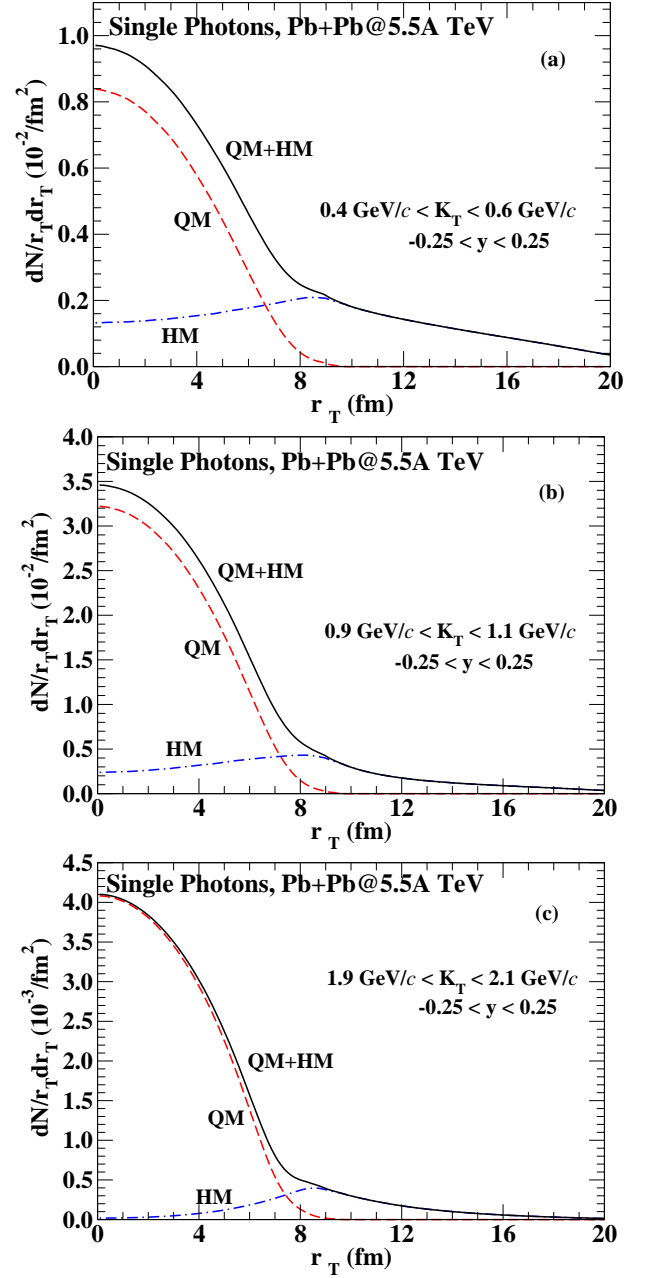


FIG. 9: (Colour on-line) The radial dependence of the source-distribution function for emission of photons having transverse momenta (a) 0.5, (b) 1.0, and (c) 2.0 GeV/c at LHC energy.

dying out of the quark source and a delayed build-up of hadronic source in time (Fig. 10) are seen to emerge very clearly.

V. SENSITIVITY TO τ_0 AND T_C

We have seen that the final correlation is decided by the relative contributions from the quark-matter which occupies a smaller volume and is shorter lived, and those

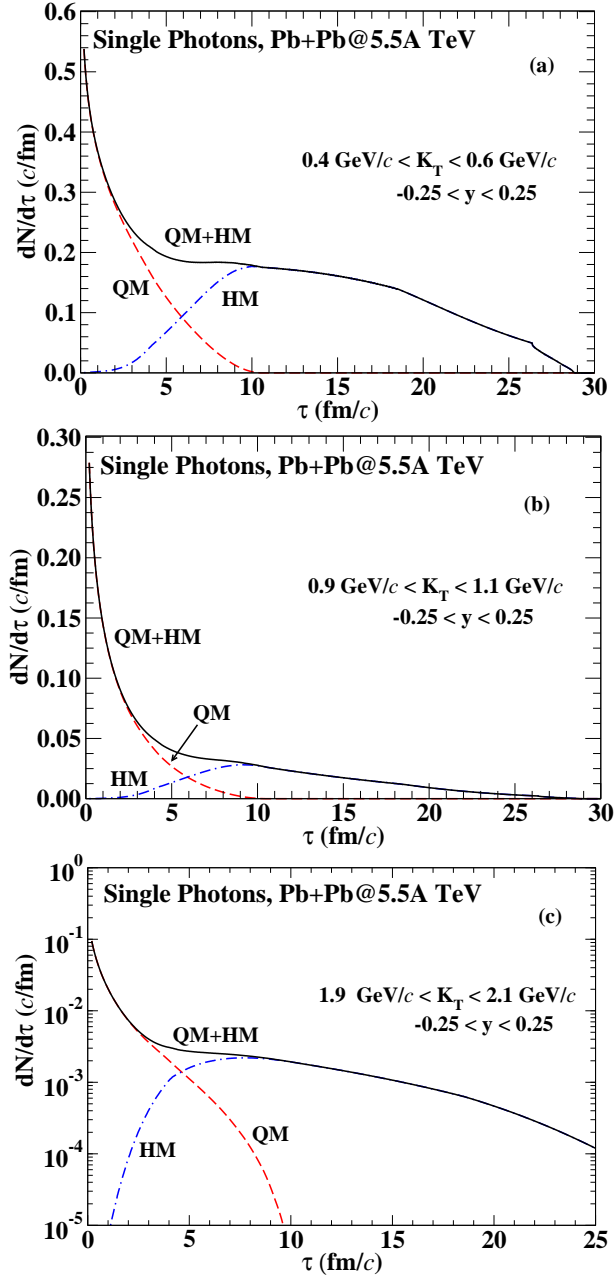


FIG. 10: (Colour on-line) The temporal dependence of the source distribution function for radiation of photons having transverse momenta of (a) 0.5, (b) 1.0, and (c) 2.0 GeV/c at LHC energy.

from the hadronic matter, which occupies to a larger volume and lives longer.

If the system thermalizes quickly, the initial temperature would be large. One can test the sensitivity of the results to the formation time of the plasma, by considering systems with identical entropy, but having varying formation times (τ_0). The fractional contribution of the quark matter, (I_Q) will increase with decreasing τ_0 . In Fig. 11 we have shown the τ_0 dependence of the outward and longitudinal correlations at RHIC. The sideward cor-

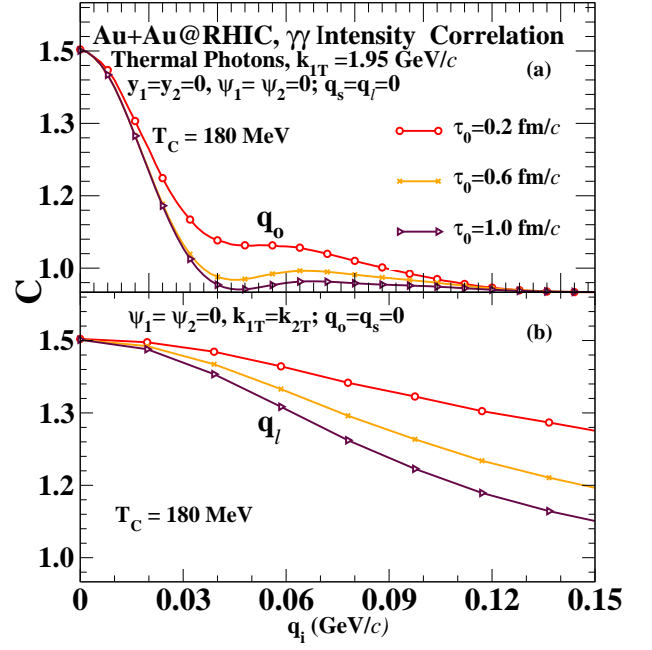


FIG. 11: (Colour on-line) τ_0 dependence of (a) the outward and (b) the longitudinal correlation function at RHIC.

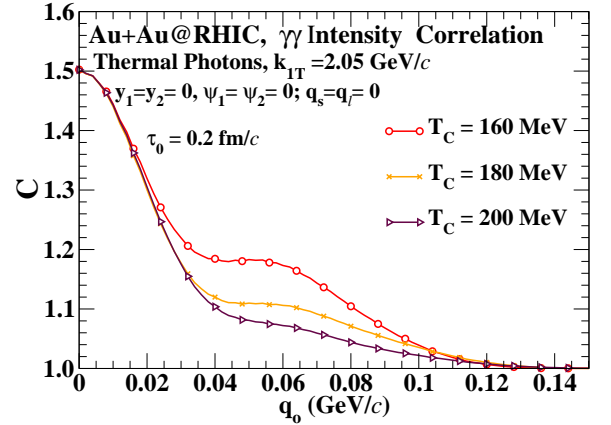


FIG. 12: (Colour on-line) T_C dependence of the outward correlation function at RHIC.

relation function did not show any perceptible change due to the variation of τ_0 and is not shown here. We must add here that choosing a large τ_0 would necessitate the inclusion of the pre-equilibrium contribution to the photons [10] which must surely be there, at least at larger K_T . The jet-conversion mechanism [11] is also likely to contribute at larger K_T . These contributions, per-force have their origin in the deconfined matter and their spatial distribution is not likely to be very different from the early stages of the initial distributions assumed here. Their contributions would increase I_Q in these studies, which in turn could mimic an effectively smaller τ_0 . This would still be useful, as it will amount to getting an effective τ_0 after which the hydrodynamics can be applied.

However these discussions open the door to another interesting and potentially powerful observation, perhaps, with a far reaching implication. We have already noted the sensitivity of the fractions of the contributions of the quark-matter (I_Q) and the hadronic matter (I_H) to the transition temperature at both RHIC and LHC (see Figs. 3 and 8). In Fig. 12 we show our results for the sensitivity of the outward correlation at RHIC to the transition temperature. Recalling that an increase in the transition temperature leads to a decrease in I_Q , and that the quark matter contribution has a smaller R_o the change in the interference pattern seen at larger q_o is easily understood.

It is felt that the results shown here should be valid whenever the correlations arise from contributions from two sources separated in space and time (see e.g., Ref. [21]). The contribution of the two sources to the correlation function also provides a natural explanation for the failure of the earlier studies [13] to find a simple Gaussian parametrization for it.

VI. SUMMARY

To summarize, the rich structure of the sideward, outward, and longitudinal correlation functions for intensity

interferometry of thermal photons at RHIC and LHC energies is calculated. The correlation functions are marked by a very distinctive interference between the photons from the quark and the hadronic matter, which is most clearly visible in the outward correlation. We have calculated the transverse momentum dependence of the correlation radii and the duration of the emission and tried to understand their behaviour by calculating the spatial and the temporal distribution of the sources and their contributions. The study has thrown open an interesting possibility of determination of transition temperature and the formation time of the plasma. Finally, we would like to add that even though several earlier studies have also talked of the two sources of photons (quark and hadronic matter) contributing to the correlation function, the present work, as far as we know, is the first attempt to study their interference in relativistic heavy ion collisions.

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- [1] X. N. Wang, Phys. Rev. C **63**, 054902 (2001); M. Gyulassy, I. Vitev, and X. N. Wang, Phys. Rev. Lett. **86**, 2537 (2001).
 - [2] K. Adcox *et al.* [PHENIX Collaboration], Phys. Rev. Lett. **88**, 022301 (2002); J. Adams *et al.* [STAR Collaboration], Phys. Rev. Lett. **91**, 172302 (2003).
 - [3] C. Adler *et al.* [STAR Collaboration], Phys. Rev. Lett. **87**, 182301 (2001); *ibid* **89**, 132301 (2002); *ibid* **90**, 032301 (2003); S. S. Adler *et al.* [PHENIX Collaboration], Phys. Rev. Lett. **91**, 182301 (2003).
 - [4] P. Huovinen, P. F. Kolb, U. Heinz, P. V. Ruuskanen, and S. A. Voloshin, Phys. Lett. **B503**, 58 (2001); D. Teaney, J. Lauret, and E. V. Shuryak, nucl-th/0110037.
 - [5] V. Greco, C. M. Ko, and P. Levai, Phys. Rev. Lett. **90**, 202302 (2003); R. J. Fries, B. Müller, C. Nonaka, and S. A. Bass, Phys. Rev. Lett. **90**, 202303 (2003).
 - [6] M. M. Aggarwal *et al.* [WA98 Collaboration], Phys. Rev. Lett. **85**, 3595 (2000).
 - [7] D. K. Srivastava and B. Sinha, Phys. Rev. C **64**, 034902 (2001); R. Chatterjee, D. K. Srivastava, and S. Jeon, Phys. Rev. C **79**, 034906 (2009) and references there in.
 - [8] T. Dahms [PHENIX Collaboration], J. Phys. G **35**, 104118 (2008); A. Adare *et al.* [PHENIX Collaboration], arXiv:0804.4168 [nucl-ex].
 - [9] D. G. d'Enterria and D. Peressounko, Eur. Phys. J. C **46**, 451 (2006).
 - [10] S. A. Bass, B. Müller, and D. K. Srivastava, Phys. Rev. Lett. **90**, 082301 (2003).
 - [11] R. J. Fries, B. Müller, and D. K. Srivastava, Phys. Rev. Lett. **90**, 132301 (2003).
 - [12] M. M. Aggarwal *et al.* [WA98 Collaboration], Phys. Rev. Lett. **93**, 022301 (2004).
 - [13] D. K. Srivastava, Phys. Rev. C **71**, 034905 (2005).
 - [14] D. K. Srivastava and J. I. Kapusta, Phys. Lett. **B307**, 1 (1993); D. K. Srivastava and J. I. Kapusta, Phys. Rev. C **48**, 1335 (1993); D. K. Srivastava, Phys. Rev. D **49**, 4523 (1994); D. K. Srivastava and C. Gale, Phys. Lett. **B319**, 407 (1993); D. K. Srivastava and J. I. Kapusta, Phys. Rev. C **50**, 505 (1994); S. A. Bass, B. Müller, and D. K. Srivastava, Phys. Rev. Lett. **93**, 162301 (2004).
 - [15] A. Timmermann, M. Plümer, L. Razumov, and R. M. Weiner, Phys. Rev. C **50**, 3060 (1994); J. Pisut, N. Pisutova, and B. Tomasik, Phys. Lett. **B345**, 553 (1995), [Erratum-*ibid.* **B353**, 606 (1995)]; C. Slotta and U. W. Heinz, Phys. Lett. **B391**, 469 (1997); D. Peressounko, Phys. Rev. C **67**, 014905 (2003); J. Alam, B. Mohanty, P. Roy, S. Sarkar, and B. Sinha, Phys. Rev. C **67**, 054902 (2003); T. Renk, hep-ph/0408218.
 - [16] See e.g., U. W. Heinz and P. F. Kolb, hep-ph/0204061.
 - [17] J. Cleymans, K. Redlich, and D. K. Srivastava, Phys. Rev. C **55**, 1431 (1997).
 - [18] P. Arnold, G. D. Moore, and L. G. Yaffe, JHEP **12**, 009 (2001).
 - [19] S. Turbide, R. Rapp, and C. Gale, Phys. Rev. C **69**, 014903 (2004).
 - [20] J. Kapusta, L. McLerran, and D. K. Srivastava, Phys. Lett. **B283**, 145 (1992).
 - [21] F. M. Marques, G. Martinez, G. Matulewicz, R. W. Ostendorf, and Y. Schutz, Phys. Rept. **284**, 91 (1997); F. M. Marques *et al.* Phys. Rev. Lett. **73**, 34 (1994); Phys. Lett. **B349**, 30 (1995); Phys. Lett. **B394**, 37 (1997).